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Active Power Conditioner Based on a Voltage Source Converter for Harmonics and Negative Sequence Components Compensation in Electrified Railway Systems

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Abstract

The electrification of railway systems has always presented major challenges to the public electrical power systems. Electric locomotives are usually supplied by a single-phase AC catenary, causing unbalance and the appearance of negative sequence components (NSCs) in the three-phase electrical power grids. In addition, the traction power system of the electric locomotive is usually comprised by uncontrolled rectifiers to convert AC voltage to DC voltage, which produces high levels of current harmonics. Consequently, the operation of electric locomotives causes serious power quality problems to the public electrical power systems. This paper evaluates the use of Shunt Active Power Conditioners (SAPCs) to compensate power quality problems in single-phase 25 kV, 50 Hz railway traction substations, when using the conventional V/V or the Scott traction power transformer between the catenary and the public electrical power systems.

Keywords: Active Power Conditioner; Current Harmonics; Electric Locomotives; Negative Sequence Components; Power Quality.

1. Introduction

Power quality is one of the most important challenges in modern electrical power systems. The poor Power Quality can cause enormous economic losses to the industrial and commercial facilities. In Europe, Power Quality problems cost more than €150 billion per year (R. Targosz et al., 2012). The use of more diode rectifiers, thyristor power converters, arc furnaces, switching power supplies and other non-linear loads, causes serious power quality problems in the electric power grids (A. Bachry et al. 2003). Furthermore, the electrification of railway traction power systems also causes several adverse impacts in the public electrical grid power quality, such as current harmonics, current imbalances and NSCs of currents (Gazafrudi et al., 2015 and Tanta et al., 2017).
In order to mitigate the effects of NSCs, V/V traction power transformers (unbalanced transformers) are normally used to alternate the traction load between the three-phases, making the public electrical power grids as balanced as possible (Perin et al., 2015). On the other hand, Scott traction power transformers (balanced transformers) can be used to achieve the balance between currents phases (Luo et al., 2011). However, nowadays, the only effective way to mitigate the aforementioned negative effects is the use of power electronics converters. In the last years, many power electronics solutions have been developed to compensate the harmonics and NSCs in the electrified railways systems (Krastev et al., 2016). The Shunt Active Power Conditioners (SAPCs) have proved to be an effective solution in compensation of the currents harmonics, NSCs and reactive power in the industrial facilities (J. G. Pinto et al., 2012). The compensation capabilities of the SAPCs are strictly related to the hardware topology of the power converters and the applied control algorithms. In terms of power converters topologies, there are two main groups: the Current Source Inverters (CSI) and the Voltage Source Inverters (VSI) (J. G. Pinto et al., 2012-2). Despite some advantages of the CSI converters, in the last years, it is evident a significant supremacy in the development and use of the VSI, mainly due to the lower cost per energy storage capacity of the capacitors used in the VSI DC-link (J. G. Pinto et al., 2012-2). In terms of control algorithms, the main differences are between their implementation in the time domain or in the frequency domain. Control algorithms implemented in the time domain and based on the instantaneous active and reactive power theory (*p-q* theory) are known to be a proficient solution for SAPCs (Edson H. Watanabe et al., 2010).
This paper presents a study on the application of SAPCs combined with V/V and Scott traction power transformer to compensate the current harmonics, the NSCs and the reactive power of electrified railway systems. In the scope of this paper, the SAPC is based on a two-level three-phase VSI with a control algorithm based on the *p-q* theory. The paper is organized as follows: Section 1 presents the main concepts of the subject and a review of the state-of-the-art. Section 2 describes the SAPC hardware topology and its application to railway traction substations. Section 3 describes in detail, the SAPC functionalities and control algorithms. Section 4 presents the test scenarios used to validate the SAPC and to evaluate its performance. Finally, Section 5 presents the main conclusions of this work.

2. Application of Active Power Conditioners in Railway Systems

The SAPC is composed by a three-phase three-leg power converter with a capacitor in the DC-side. The converter is connected to the electrical power grid through three coupling inductors and a step-down transformer. It is important to highlight that this paper is focusing on the study of the SAPC application to compensate current harmonics and NSCs in the electrified railways systems regardless the hardware of the power converter. Therefore, the simplest topology was adopted, however, it is also possible to obtain identical results with other topologies of the converter, for instance, using multilevel converters. Fig. 1 presents the electric schematic of the SAPC connected to a railway traction substation.
In order to reduce the current imbalance in the power grid side, typically railway traction substations use V/V or Scott power transformers to supply two separated catenaries with a neutral section. The adoption of V/V and Scott power transformers is justified by a significant reduction in the power grid NSCs when both the catenary sections are loaded equality. To evaluate the performance of the SAPC, the two types of transformers were considered and a comprehensive comparison of the results with each one of the power transformer schemes is presented. As shown in Fig. 1, the SAPC is connected in parallel with the traction power transformer. The parallel connection signifies that the SAPC can be connected or disconnected without disturbing the operation of the traction substation. Therefore, the robustness and readiness of the railway substation will not be affected by the operation of the SAPC. On the other hand, the SAPC does not have an internal power supply system, meaning that this device has a neutral contribution in terms of the active power, i.e., the SAPC will not absorb or provide active power to the electrical power grid. As the active power necessary to the loads flows directly to the catenary through the V/V or the Scott power transformer, the volt-ampere (VA) rate of the SAPC can be significantly lower than the traction substation VA rate.

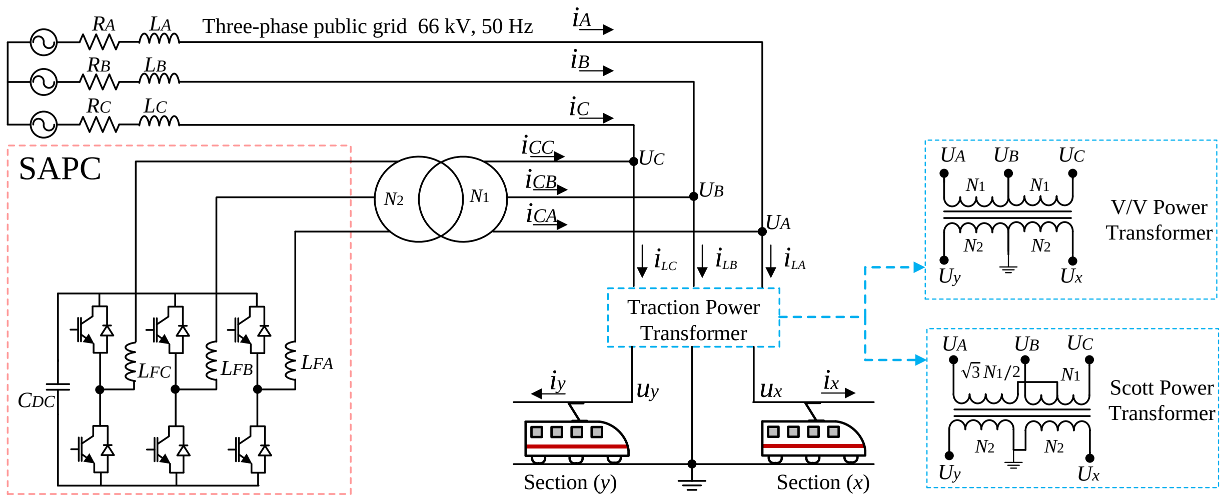

Fig. 1 Application of a Shunt Active Power Conditioner (SAPC) in a Railway Traction Substation.

3. SAPC Control Algorithms

The controller of the SAPC presented in this paper uses the instantaneous reactive power theory, which is also known as *p-q* theory (Akagi et al., 1983). The *p-q* theory is largely applied in the implementation of the active power filters over the last years, and, normally, it provides good results even in several distinct electrical installations with various types of loads (J. G. Pinto et al., 2009). The *p-q* theory is applied in the α-β coordinates referential, and so, the power grid voltages (u_A, u_B, u_C) and the load currents (i_{LA}, i_{LB}, i_{LC}) must be translated to (u_α, u_β) and to (i_α, i_β) by applying the Clarke transformation expressed in (1) and (2).

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \sqrt{2/3} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{2/3} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{LA} \\ i_{LB} \\ i_{LC} \end{bmatrix} \tag{2}$$

Using the power grid voltages (u_α, u_β) and load currents (i_α, i_β) in the α-β referential, the instantaneous real power (p), and the instantaneous imaginary power (q) are calculated using (3) and (4).

$$p = u_\alpha \cdot i_\alpha + u_\beta \cdot i_\beta \tag{3}$$

$$q = u_\beta \cdot i_\alpha - u_\alpha \cdot i_\beta \tag{4}$$

Each one of the instantaneous power components defined by the *p-q* theory can be decomposed into average and oscillating parts. The physical meaning of each of the instantaneous powers is:

- $\bar{p}$ - Average value of the instantaneous real power p. Corresponds to the energy per time unit transferred from the power source to the load, in a balanced way through the three-phases.
- $\tilde{p}$ - Oscillating value of the instantaneous real power p. It is the energy per time unity that is exchanged between the power source and the load, through the three-phases. This component is caused by imbalances in the voltages, imbalances in the currents and harmonics.
- q - The instantaneous imaginary power. Corresponds to the power that is exchanged between the phases of the load. This component does not imply any transference of energy between the power source and the load, but is responsible for the existence of undesirable currents.

Normally, in a power system, only the average value of the instantaneous real power ($\bar{p}$) is desired, and the other power components can be compensated by using the SAPC. In order to calculate the reference currents that the SAPC should produce, it is necessary to separate the desired power components from the undesired ones. The undesired power components are denominated p_x and q_x. In addition to the instantaneous power components defined by the *p-q* theory, there is also a component, p_{reg}, which is used to regulate the capacitor voltage in the DC-side of the power converter. This regulation is done by a Proportional-Integral (PI) controller, and the error between the reference voltage (U_{ref}) and the voltage measured at the DC-side of the converter (U_{DC}). The power component, p_{reg}, corresponds to a real power component and, in practice, it corresponds to the SAPC operation losses. As long as the SAPC do not have an internal power supply system, p_{reg} must be supplied by the power grid in a balanced way through the three-phases, and therefore, this power component is included in the calculation of p_x. The values of the power components that the SAPCs should produce are given by (5) and (6).

$$p_x = \tilde{p} - p_{reg} \tag{5}$$

$$q_x = q \tag{6}$$

The undesired power components p_x and q_x are then used to determine the compensation currents in the α-β referential using (7).

$$\begin{bmatrix} i_{c\alpha}\,* \\ i_{c\beta}\,* \end{bmatrix} = \frac{1}{u_\alpha^2 + u_\beta^2} . \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix} \cdot \begin{bmatrix} p_x \\ q_x \end{bmatrix} \tag{7}$$

The compensation currents in the *a-b-c* referential (i_{CA}*, i_{CB}*, i_{CC}*) are determined by applying the inverse Clarke transformation as demonstrated in (8):

$$\begin{bmatrix} i_{CA}\,* \\ i_{CB}\,* \\ i_{CC}\,* \end{bmatrix} = \sqrt{2/3} \cdot \begin{bmatrix} 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{c\alpha}\,* \\ i_{c\beta}\,* \end{bmatrix} \tag{8}$$

The application of the *p-q* theory will produce compensation currents that result in a constant instantaneous real power from the electrical power grid. In three-phase systems with distorted and/or unbalanced voltages, it is not possible to have at the same time constant real power and sinusoidal balanced currents. Therefore, when the electrical grid voltages are distorted and/or unbalanced, the operation of the SAPCs results in distorted and/or unbalanced currents. In some applications, instead of constant instantaneous real power, it is preferable to obtain sinusoidal and balanced currents from the power grid. To achieve this goal, it is possible to do a little modification to the *p-q* theory consisting in replacing in (1) the power grid voltages by the positive sequence of the fundamental component of these voltages. To obtain the positive sequence of the fundamental component of the power grid voltages, it can be used the digital Phase-Locked Loop (PLL) proposed in L. G. B. Rolim et al. (2006). The *p-q* theory modification to obtain sinusoidal and balanced currents was already successfully applied to a VSI SAPC (J. G. Pinto et al., 2013).

4. SAPC Simulation Results

In order to study the application of SAPC in railways systems, a simulation model of the SAPC and the traction substation was developed using the PSIM 9.1 software tool. To evaluate correctly the performance of the SAPC, three simulation scenarios using the V/V power transformer, besides other three scenarios using the Scott power transformer, were considered. In the first scenario, a V/V traction transformer with the two catenary sections were equally loaded. The second scenario evaluates the behavior of the SAPC with the V/V traction power transformer and when only section *x* of the catenary was fully loaded (section *y* of the catenary without any load). The third scenario evaluates the SAPC behavior during an abrupt load transient in one of the catenary sections with the V/V traction power transformer. All of the above-mentioned scenarios were repeated using a Scoot power transformer in the connection between the electric power grid and the catenary.

4.1. Evaluation of the SAPC with a V/V traction power transformer and equally loaded catenary sections

In this case study, it was considered a V/V traction power transformer when two sections of the catenary (section *x* and section *y*) are equally loaded. To obtain a more realistic scenario, the load in each of the catenary sections is composed by linear and by non-linear (single-phase rectifier with RL series load in the DC-side) with total power of 7.5 MW, to simulate a real set of locomotives. In Fig. 2, the simulation results are presented for this scenario, and Table 1 presents some important parameters of the simulation results. Fig. 2 (a) shows the currents in the two catenary sections (i_x and i_y), the currents in the electrical power grid phases (i_A, i_B and i_C), the instantaneous real power of the power grid (p), the three-phase electric power grid active power (P_3) and the three-phase apparent power (S_3), and the Positive Sequence Components (PSC) and NSC of the power grid currents fundamental component (50 Hz) without the SAPC. Fig. 2 (b) shows the same variables but with the SAPC in operation.

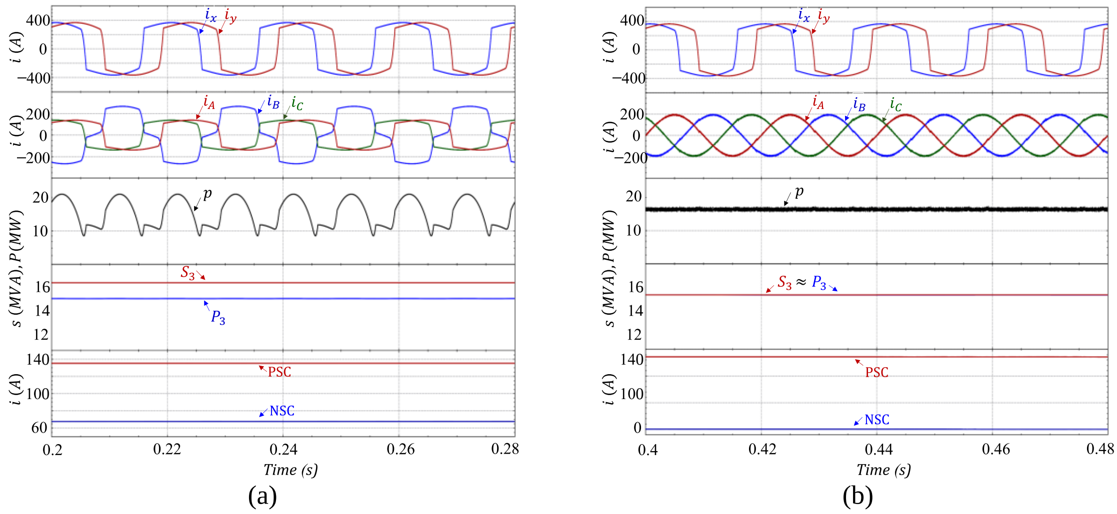

Fig. 2 Simulation results with V/V traction power transformer and equally loaded catenary sections: (a) Without SAPC; (b) With SAPC.

The SAPC is installed in parallel with the traction substation with the objective of improve the power quality in the three-phase power grid side, without interfering the loads operation. Therefore, the catenary currents remains the same, with and without the SAPC operation, and presents an RMS value of 325 A and a Total Harmonic Distortion in percentage of the fundamental ($THD_{\%f}$) slightly greater than 32%. Although the two catenary sections are equally loaded, which is the favorable situation with a V/V power transformer, it is visible that without the SAPC, the power grid currents (i_A, i_B and i_C) are distorted and unbalanced, resulting on a NSC/PSC ratio of 50%. Although the currents in phase *A* and phase *B* present the same RMS values, resulting in similar apparent power in each one of these phases, the apparent power in phase *B* is significantly higher.

Table 1. Operation parameters with V/V traction power transformer and equally loaded catenary sections.

Variable	Without SAPC	With SAPC
i_x / THDi_X%f	325 A / 32%	325 A / 32%
i_y / THDi_Y%f	325 A / 32%	325 A / 32%
i_A / THDi_A%f	123 A / 32%	136 A / 3%
i_B / THDi_B%f	207 A / 19%	136 A / 3%
i_C / THDi_C%f	123 A / 32%	136 A / 3%
P_A / S_A	4.2 MW / 4.7 MVA	5.2 MW / 5.2 MVA
P_B / S_B	7.6 MW / 7.9 MVA	5.2 MW / 5.2 MVA
P_C / S_C	3.4 MW / 4.7 MVA	5.2 MW / 5.2 MVA
P3 / S3	15.2 MW / 17.3 MVA	15.5 MW / 15.5 MVA
NSC / PSQ	67.6 A / 135 A	0.3 A / 135.9 A
SAPC Apparent Power	--	9.2 MVA

With respect to active power, it is visible in the table 1 that the value is significantly different in all the three phases. In terms of instantaneous power, it is visible that without the SAPC, this variable presents big oscillations, which are translated into oscillating torques in the electrical generators causing problems of vibration and other mechanical stress to these machines. With the SAPF in operation, the power grid currents become balanced and almost sinusoidal, the apparent power is equally distributed by the three-phases and becomes equal to the active power, meaning that the reactive power was successfully compensated, the NSC/PSC ratio is reduced to less than 0.3% and the instantaneous power becomes almost constant. The only negative effect of the SAPC operation is a very slight increase in the total active power, of about 2.2%, resulting from the losses in the power electronic converter and the coupling inductors as well.

4.2. Evaluation of the SAPC with V/V traction power transformer and unequally loaded catenary sections

In this case study, it was considered a V/V traction power transformer and the section y of the catenary supplies linear and non-linear load of 7.5 MW and section x of the catenary is unloaded. This scenario represents a situation where section y supply a locomotive and there are no locomotives in section x. Fig. 3 presents the simulation results for this scenario, and Table 2 presents the relevant parameters of the simulation.

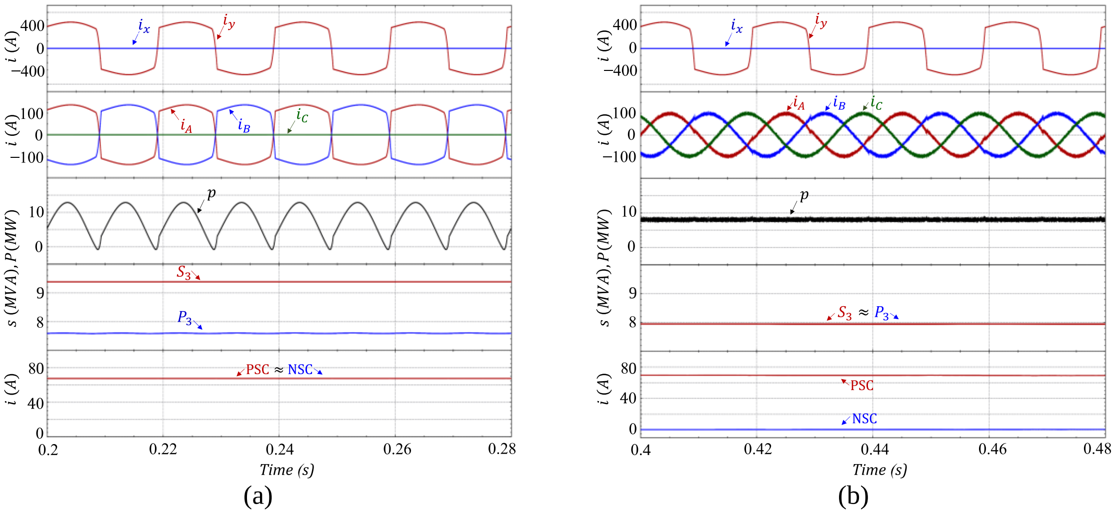

Fig. 3 Simulation results with Scott transformer and unequally loaded catenary sections: (a) Without SAPC; (b) With SAPC.

As the section x of the catenary was unloaded, the current in the section y of the catenary presents an RMS value of 325 A and a $THD_{\%f}$ slightly greater than 32%, while the current in section x is near zero and the $THD_{\%f}$ was not significant. Without the SAPC the power grid current in phase C is zero, meaning that this phase do not contribute to supply the load, resulting in a huge NSC/PSC ratio of 100%. As the currents in phase A (i_A) and phase B (i_A) present the same RMS values, the apparent power in these phases are equal. However, in terms of active power the phase A has a greater contribution. The total apparent power is significantly greater than the active power, meaning that the circuit is consuming a significant amount of the reactive power.

Table 2. Operation parameters with V/V traction power transformer and unequally loaded catenary sections.

Variable	Without SAPC	With SAPC
i_x / THDi_X%f	0.01 A / n.a.	0.01 A / n.a.
i_y / THDi_Y%f	325 A / 32%	325 A / 32 %
i_A / THDi_A%f	325 A / 32%	69.2 A / 5.5%
i_B / THDi_B%f	325 A / n.a.	69.9 A / 5.2%
i_C / THDi_C%f	0.01 A / n.a.	69.4 A / 5.1%
P_A / S_A	4.2 MW / 4.7 MVA	2.64 MW / 2.64 MVA
P_B / S_B	3.4 MW / 4.7 MVA	2.63 MW / 2.63 MVA
P_C / S_C	0.001 MW / 0.001 MVA	2.63 MW / 2.63 MVA
P3 / S3	7.6 MW / 9.3 MVA	7.9 MW / 7.9 MVA
NSC / PSQ	67.6 A / 67.6 A	0.4 A / 69.4 A
SAPC Apparent Power	--	8.6 MVA

The instantaneous power presents huge oscillations, becoming even negative for a few moments. This means that during the moments in which the instantaneous power is negative the energy is flowing from the load to the power grid. In the other meaning, the electric power grid is exchanging energy with the load, resulting in an increase of the losses in the energy transference. With the SAPC in operation, the electric power grid currents become balanced and sinusoidal, the active power is balanced by the three-phases and the reactive power was compensated. The NSC/PSC ratio is reduced from 100% to less than 0.6% and the instantaneous power becomes almost constant.

4.3. Evaluation of the SAPC with a V/V traction power transformer during a transient catenary load

In the previous study cases, the operation of the SAPC was evaluated considering that the system parameters are constant and in steady state. To evaluate the performance of the SAPC during the transient conditions, it was considered a scenario in which the load in the section x of the catenary suffers an abrupt change from 7.5 MW to half of this value at the instant t = 0.5 s. The simulation results of this scenario are presented in Fig. 4. As it is possible to see, before the transient, the currents in the two catenary sections present the same amplitude and at t = 0.5 s the section x current is reduced to the half of its original value. By observing the electric power grid currents, it is possible to see that they remain balanced and practically sinusoidal during the transient state. Looking to the instantaneous power, it is also visible the reduction from the initial value to the new one. During the transient, both of the NSC and the reactive power remain compensated.

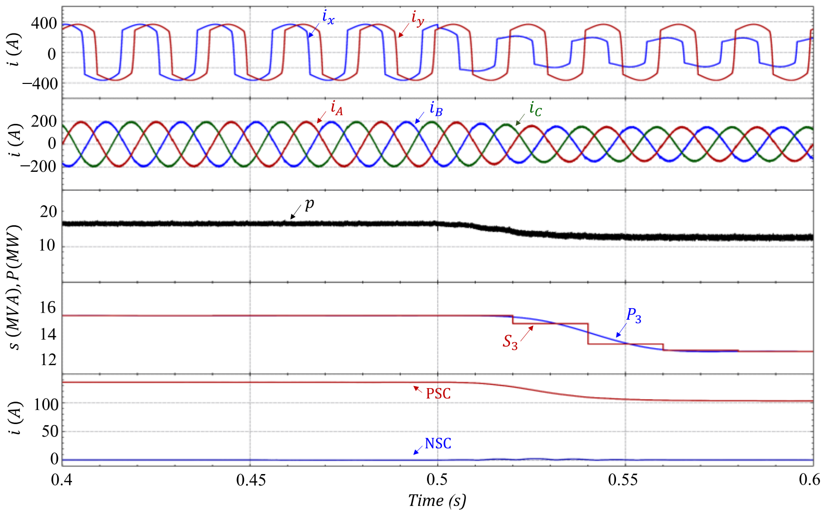

Fig. 4 Operation of the SAPC with a V/V traction power transformer during an abrupt load change transient at 0.5 s.

4.4. Evaluation of the SAPC with a Scott traction power transformer and equally loaded catenary sections

To study the performance of the SAPC operating with a Scott traction power transformer, it was considered a scenario similar to the one used in the item 4.1, but using the Scott traction power transformer instead of the V/V one. With the two catenary sections equally loaded, it is expectable that the RMS values of the power grid currents (i_a, i_b and i_c) are similar in the three-phases and that the apparent power and the active power are equally distributed by the three-phases. In fact, this is the main advantage of the Scott configuration comparing to the V/V transformer (with the two catenary sections equally loaded, the power is balanced through the three-phases). However, as the locomotives are non-linear loads, the problems related with current harmonics remains even with balanced loaded catenary sections. Fig. 5 and Table 3 present the simulation results for this scenario. As it is possible to see in Fig. 5 (a), which refers to the results without SAPC, the currents in the two catenary sections are similar. Although the electric power grid currents present different waveforms, they have the same RMS value and the same $THD_{\%f}$. The difference in the waveform is due to the differences in the phases of the harmonics. In terms of instantaneous power (p), it is visible that without the SAPC this variable presents considerable oscillations. With the SAPF in operation, results presented in the Fig. 5 (b), the power grid currents (i_a, i_b, and i_c) become sinusoidal and balanced. In terms of powers, by consulting Table 3, it is visible a significant reduction in the apparent power (S_3), resulting from the compensation of the reactive power and very slightly increase in the active power (P_3) caused by the SAPC operation losses.

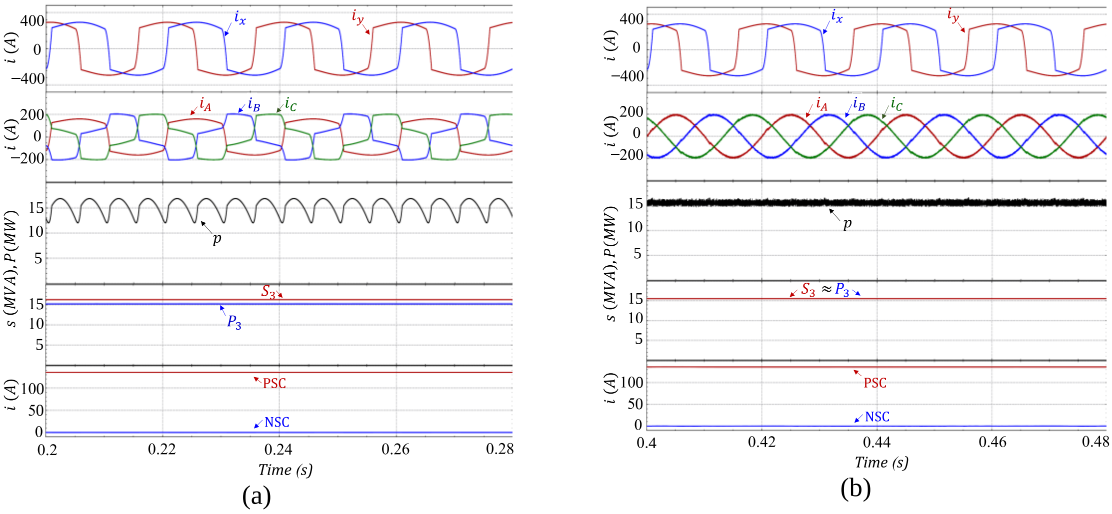

Fig. 5 Simulation results with a Scott transformer and equally catenary sections: (a) Without SAPC; (b) With SAPC.

Table 3. Operation parameters with Scott transformer and equally loaded catenary sections.

Variable	Without SAPC	With SAPC
i_x / THDi_X%f	325 A/ 32%	325 A/ 32%
i_y / THDi_Y%f	325 A/ 32%	325 A/ 32%
i_A / THDi_A%f	142 A/ 32%	136 A/ 3%
i_B / THDi_B%f	142 A/ 32%	136 A/ 3%
i_C / THDi_C%f	142 A/ 32%	136 A/ 3%
P_A / S_A	5.1 MW / 5.42 MVA	5.18 MW / 5.18 MVA
P_B / S_B	5.1 MW / 5.42 MVA	5.18 MW / 5.18 MVA
P_C / S_C	5.1 MW / 5.42 MVA	5.18 MW / 5.18 MVA
P3 / S3	15.2 MW / 16.3 MVA	15.53 MW / 15.54 MVA
NSC / PSQ	0.2 A / 135 A	0.06 A / 136 A
SAPC Apparent Power	--	5.8 MVA

4.5. Evaluation of the SAPC with a Scott traction power transformer and unequally loaded catenary sections

In this case study, it was considered a Scott traction power transformer and the section *y* of the catenary supplies linear and non-linear load of 7.5 MW and section *x* of the catenary is unloaded. The simulation results from this scenario are depicted in the Fig. 6 and in the Table 4.

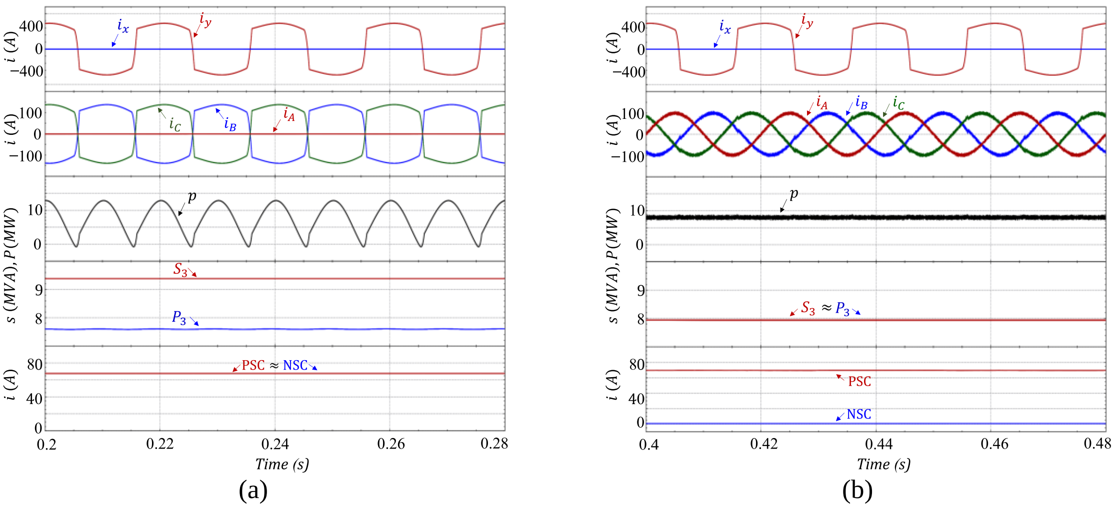

Fig. 6 Simulation results with a Scott transformer and unequally loaded catenary sections: (a) Without SAPC; (b) With SAPC.

As it is visible in Fig. 6 (a) with unequally loaded catenary sections the arrangement of the Scott traction power transformer is not as effective as in the previous case study, and the power grid currents (i_a, i_b, and i_c) present very different RMS values contributing to a huge NSC/PSC ratio of 100%. The instantaneous power presents huge oscillations, becoming even negative for a few moments and contributing to the increase of losses in the energy transference. The total apparent power (S_3) is significantly greater than the active power (P_3), meaning that the circuit is consuming a significant amount of the reactive power. With the SAPC in operation, the electric power grid currents become balanced and sinusoidal and the NSC/PSC ratio is reduced from 100% to less than 0.6%. The active power is equally distributed by the three phases ($P_A = P_B = P_C$) and reactive power was compensated. The instantaneous power (p) becomes almost constant.

Table 4. Operation parameters with a Scott transformer and unequally loaded catenary sections.

Variable	Without SAPC	With SAPC
i_x / THDi_X%f	0.03 A / n.a.	0.03 A / n.a.
i_y / THDi_Y%f	325 A / 32%	325 A / 32%
i_A / THDi_A%f	0.01 A / n.a.	69.4 A / 5%
i_B / THDi_B%f	123 A / 32%	69.2 A / 5%
i_C / THDi_C%f	123 A / 32%	69.9 A / 5%
P_A / S_A	0.001 MW / 0.001 MVA	2.64 MW / 2.64 MVA
P_B / S_B	4.2 MW / 4.7 MVA	2.63 MW / 2.63 MVA
P_C / S_C	3.4 MW / 4.7 MVA	2.66 MW / 2.66 MVA
P3 / S3	7.6 MW / 9.4 MVA	7.9 MW / 7.9 MVA
NSC / PSQ	67.7 A / 67.7 A	0.6 A / 69.5 A
SAPC Apparent Power	--	8.6 MVA

4.6. Evaluation of the SAPC with a Scott traction power transformer during a transient catenary load

The last case study was conducted to evaluate the performance of the SAPC operating with a Scott traction power transformer during the transient conditions. For that purpose, it was considered a scenario in which the load in the section x of the catenary suffers an abrupt change from 7.5 MW to half of this value at the time instant $t = 0.5$ s. The simulation results for this scenario are presented in the Fig. 7. As it is possible to see, before the transient state, the currents in the two catenary sections present the same amplitude and at $t = 0.5$ s the current in the section x of the catenary reduces to half of its original value. The behavior of the system during this test was very similar as the obtained in the item 4.3 with the V/V transformer. This is, the power grid currents (i_A, i_B, and i_C) remain balanced and practically sinusoidal during the transient and that the amplitude reduces softly to the new value after the transient. This smooth variation in the operation conditions is also visible in the evolution of the instantaneous power p. During all the simulation period, the SAPC fully compensates the reactive power and maintain the NSC near to zero.

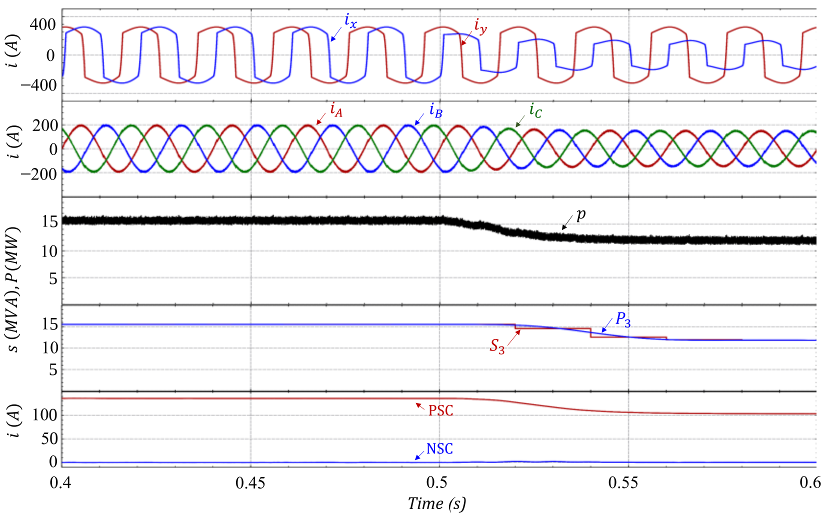

Fig. 7 Operation of the SAPC with Scott power transformer during abrupt load change transient at 0.5 s.

5. Conclusions

This paper presents a study that evaluates the use of Shunt Active Power Conditioners (SAPCs) applied to railway V/V and Scott traction power transformers in 25 kV, 50 Hz single-phase catenary systems to compensate the current harmonics and the negative sequence components (NSCs) in the public electrical power grid. The study considered six different scenarios, considering both equally and unequally loaded catenary sections, besides load transients, with both transformers configurations. As demonstrated, the SAPC is extremely competent in all the tested conditions, presenting an excellent performance in the compensation of current harmonics, current imbalances and reactive power. The operating performance of the SAPC with both types of power transformers was very similar, and the final results obtained were equivalent. The only difference worth mentioning is related with the scenario when the two catenary sections are equally loaded, in which, although the final results are very similar, the SAPC operates with a much lower volt-ampere (VA) rating when using the Scott traction power transformer. This is explained by the fact that the arrangement of the Scott transformer already balances the power through the three-phases, facilitating the action of the SAPC. Thus, it is possible to technically conclude that, the SAPC is an effective solution to improve power quality in the electrified railways systems by compensating the reactive power, current harmonics and the current unbalance, which are typically present in these systems. The main additional advantage of the SAPC is its parallel connection with the traction power, which means that the equipment can be turned ON/OFF without disturbing the normal operation of the traction substations, then maintaining the robustness and readiness required in railways systems.

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